Novae as a Mechanism for Producing Cavities around the Progenitors of SN 2002ic and Other SNe Ia

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ABSTRACT

We propose that a nova shell ejected from a recurrent nova progenitor system created the evacuated region around the explosion center of SN 2002ic. In this picture, periodic shell ejections due to nova explosions on a white dwarf sweep up the slow wind from the binary companion, creating density variations and instabilities that lead to structure in the circumstellar medium (CSM). Our model naturally explains the observed gap between the supernova explosion center and the CSM in SN 2002ic, accounts for the density variations observed in the CSM, and resolves the coincidence problem of the timing of the explosion of SN 2002ic with respect to the apparent cessation of mass-loss in the progenitor system. We also consider such nova outburst sweeping as a generic feature of Type Ia supernovae with recurrent nova progenitors.

Subject headings: novae — stars: winds — supernovae — supernovae: individual (SN 2002ic)

1. Introduction

The remarkable supernova (SN) SN 2002ic has opened a window into the nature and progenitors of Type Ia supernovae (SNeIa). Discovered by Wood-Vasey (2002) and identified from a pre-maximum spectrum as a SNIa by Hamuy et al. (2002), SN 2002ic appeared to be a normal SNIa from $\sim$ 5–20 days after explosion (there were no observations during the first $\sim$ 5 days after explosion; Wood-Vasey et al. 2004). Around 22 days after explosion, SN 2002ic brightened to twice the luminosity of a normal SNIa and showed strong Hα emission (Hamuy et al. 2003). The hydrogen emission and excessive brightness were attributed to interaction with a substantial circumstellar medium (CSM; Hamuy et al. 2003; Deng et al. 2004; Wood-Vasey et al. 2004). The standard brightness before 22 days and the suddenness of the

brightening at that time implied that the original SN explosion expanded into a region with little CSM, i.e., a cavity, and then suddenly encountered a region with significant CSM. At 60 days after explosion, the lightcurve of SN 2002ic rose again (Hamuy et al. 2003; Wood-Vasey et al. 2004) in a manner consistent with a second increase in the CSM density. SN 2005gj appears to be another member of this class (Prieto et al. 2005), and SN 1997cy is now widely believed to have been a SN 2002ic-like event as well (Hamuy et al. 2003; Deng et al. 2004; Wood-Vasey et al. 2004).

In the prevailing model for the production of SNeIa, a white dwarf accretes material from a companion star until the white dwarf approaches its Chandrasekhar limit and explodes due to runaway thermonuclear fusion (for recent reviews see Hillebrandt & Niemeyer 2000; Livio 2001; Wheeler 2002). In this so-called single-degenerate model, the companion star can donate mass to the white dwarf through a variety of mechanisms, including Roche-lobe overflow, stellar winds, or expansion of the donor star to form a common envelope around both stars. Roche-lobe overflow results in a progenitor system whose environment is relatively free of hydrogen, while the other two donor processes should expel hydrogen into the surrounding medium. However, hydrogen had never been observed in a SNIa system prior to the discovery of SN 2002ic.

The observation of significant amounts of hydrogen in SN 2002ic has led to a flurry of speculation as to the nature of its progenitor system. SN 2002ic has been alternately modeled as the explosion of a white dwarf in a binary system with a post-asymptotic giant branch (AGB) companion (Hamuy et al. 2003); the explosion of the carbon-oxygen (C/O) core of a 25 $M_\odot$ star, a so-called SN I$\frac{1}{2}$ event (Iben & Renzini 1983; Hamuy et al. 2003; Imshennik & Dunina-Barkovskaya 2005); the merger of a white dwarf with the C/O core of an AGB star during a common-envelope phase (Livio & Riess 2003); and the explosion of a white dwarf in a supersoft X-ray system with delayed dynamical instability-triggered mass loss (Han & Podsiadlowski 2006). While these models each seek to explain the presence of a significant amount of hydrogen (1–6 $M_\odot$; Hamuy et al. 2003; Chugai & Yungelson 2004; Wang et al. 2004) near the site of the thermonuclear explosion, none can easily account for the size of the observed $\sim 1.7 \times 10^{15}$ cm CSM-free region immediately surrounding the explosion (Wood-Vasey et al. 2004). In this paper we provide a mechanism that explains this cavity as not due to the cessation of mass loss from the companion star but rather due to the wind material having been swept up. We propose that the progenitor of SN 2002ic was a white dwarf undergoing recurrent novae while accreting from an AGB or post-AGB companion and that the cavity surrounding the system was created by a nova ejection approximately 15 years before the supernova explosion.

We describe our model for the cavity and CSM density variations around SN 2002ic in

Sec. 2. In Sec. 3 we discuss the cavities that could be produced by prior novae in normal SNIa progenitor systems. Finally, in Sec. 4 we discuss our model in the context of the diversity and asymmetry in SNIa progenitor systems and make testable predictions.

2. A Nova Cavity around SN 2002ic

Unless material accreted onto the surface of a white dwarf in an interacting binary burns quasi-steadily, the white dwarf will experience thermonuclear flashes. These nova outbursts typically recur every $\sim 10^5$ years (Livio 1992). Immediately before a SNIa explosion, however, the white dwarf mass is near the Chandrasekhar limit, and the binary is likely to become a recurrent nova (RN), in which outbursts recur every few years to decades (e.g., Fujimoto 1982; Prialnik et al. 1982; Starrfield et al. 1985). About half of known RN are symbiotic RN, in which the white dwarf is fed by the wind from a red giant. The other half are generally close binary systems where the white dwarf is accreting mass from its companion via Roche-lobe overflow. Typical symbiotic RN consist of a white dwarf accreting from the wind of a first-ascent red giant, but AGB star donors are also possible. Such systems deposit hydrogen-rich material into their CSM through a wind from the red giant and possibly also a hot wind from the white dwarf (Hachisu et al. 1999a,b). The thermonuclear flashes from RN eject mass shells with typical velocities of $v_{\text{shell}} = 1000$–4000 km s^{-1} and masses of $M_{\text{shell}} = 10^{-7}$–$10^{-5}$ $M_\odot$ (Yaron et al. 2005). In symbiotic RN, where the white dwarf is embedded in the wind of the companion, the nova shell sweeps up this wind and creates a cavity around the binary.

The significant CSM around SN 2002ic (Hamuy et al. 2003) suggests that the progenitor of that SNIa contained an extreme AGB star rather than a first-ascent red giant companion. We thus adopt a single-degenerate system consisting of a white dwarf and a companion AGB star for our model of the progenitor system of SN 2002ic. Our nova clearing mechanism, however, is not critically dependent on the choice of companion. While early estimates of the total CSM mass in the progenitor system suggested up to 6 $M_\odot$ of circumstellar material, proper treatment of the effect of the ejecta metallicity on the X-ray absorption reduce the required CSM mass to ~ 1.1 $M_\odot$ within 3×10^{16} cm of the progenitor system (Chugai & Yungelson 2004; Nomoto et al. 2005). The mass-loss rate for a progenitor system with a wind velocity of $v_{\text{wind}} = 10\,\text{km s}^{-1}$ must thus have been close to $\dot{M}_{\text{wind}} = 10^{-3}$ $M_\odot$ yr^{-1} in the thousand years before the SNIa explosion. To model the progenitor of SN 2002ic, we thus take an AGB mass-loss rate of $\dot{M}_{\text{wind}} = 1 \times 10^{-3}$ $M_\odot$ yr^{-1} (Chugai & Yungelson 2004; Nomoto et al. 2005), a wind speed of $v_{\text{wind}} = 10$ km s^{-1} (Kudritzki & Reimers 1978; Gehrz & Woolf 1971), an ejected nova shell mass of $M_{\text{shell}} = 1 \times 10^{-6}$ $M_\odot$, and a shell velocity of

$v_{\text{shell}} = 4000$ km s^{-1}. We assume that the white dwarf is $\sim$10 AU from the companion star and that the CSM density falls off as $\rho(r_{\text{WD}}) \propto 1/r_{\text{WD}}^2$ from the red-giant wind density at the position of the white dwarf, where r_{WD} is the distance from the white dwarf. Taking a nova recurrence time of ~ 20 years, the accretion rate onto the white dwarf is $\gtrsim 5 \times 10^{-8}$, which is well within the recurrent nova mass accretion range of 3×10^{-8}–4×10^{-7} $M_\odot$ yr^{-1} (Iben 1982; Starrfield et al. 1985; Yaron et al. 2005).

A nova shell ejected into the dense material surrounding the white dwarf progenitor of SN 2002ic produces a blast wave that quickly (in minutes to hours) sweeps up enough CSM material to transition from free expansion to deceleration in the Sedov-Taylor phase. The CSM is so dense that the shock becomes radiative ~ 5000 seconds after the nova outburst and enters the momentum-conserving snowplow phase. A radiative shock moving in a $\rho \propto r^{-2}$ medium expands as $r_{\text{shock}} \propto t^{1/2}$. While Nomoto et al. (2005) suggest that far from the progenitor white dwarf the average CSM density falls off as $r^{-1.8}$, which would lead to $r_{\text{shock}} \propto t^{1/2.2}$, for simplicity and maximal generality, we treat the CSM density as following an overall r^{-2} behavior. Between the time of the last nova outburst and the SNIa explosion, the nova blast wave sweeps up the CSM and evacuates a cavity with outer radius

$$R_{\text{out}} \approx R_{\text{SP}} \left(\frac{\Delta t_{\text{nova}}}{t_{\text{SP}}} \right)^{1/2}, \tag{1}$$

where R_{SP} is the radius of the transition to the snowplow phase, t_{SP} is the time between the nova explosion and the onset of the snowplow phase of the nova blast wave, and Δt_{nova} is the time between the last nova outburst and the SNIa explosion. While the nova blast wave expands and clears out the surrounding CSM, the ongoing mass-loss from the system refills a small portion of the cavity immediately surrounding the binary.

When the white dwarf explodes as a SNIa, the SN ejecta will first encounter the mass lost from the AGB star since the last nova and then the region that was evacuated by the nova blast wave. Since the observations of SN 2002ic began 5 days after the SN explosion and no sign of CSM interaction was observed at that time, the SN ejecta must have already moved through the small region containing AGB wind material emitted since the last nova outburst. Gerardy et al. (2004) calculated that up to 2×10^{-2} $M_\odot$ of CSM can be overtaken by the SNIa ejecta at very early times with no appreciable photometric signature. If the SN ejecta swept through any existing nearby CSM in the first 5 days after explosion, the last nova outburst likely occurred within $\Delta t_{\text{nova}} \leq 5$ days $(v_{\text{SN}}/v_{\text{wind}}) \approx 14$ years of the SNIa explosion, where $v_{\text{SN}} = 10^4$ km s^{-1} is the velocity of the SNIa ejecta. This 14-year period is comparable to the typical time between outbursts of recurrent novae. If we take $\Delta t_{\text{nova}} = 14$ years, the evacuated region has an outer radius of $R(t_{\text{SN}}) \approx 1.5 \times 10^{15}$ cm, extremely close to the cavity radius of 1.7×10^{15} cm from the model of Wood-Vasey et al.

(2004). See Table 1 for a summary of these model parameters and resulting cavity size.

Both the repeated pulses of recurrent nova events and the instabilities at the shock fronts should create sizable variations in the density structure of the CSM. We interpret the secondary brightening of SN 2002ic around 60 days after the SNIa explosion as due to a CSM density enhancement from a previous nova outburst that occurred 50 years before the explosion of SN 2002ic. There are no observations of SN 2002ic from 100–200 days after explosion, so no information is available about additional large-scale density variations from earlier nova outbursts. In any event, as the system evolves, the effects of earlier nova outbursts become smeared out as hydrodynamic instabilities grow and the nova-driven shocks slow down and approach v_{wind}. Hydrodynamically unstable interactions of the nova outburst shells with the stellar wind outflow could produce the oft-discussed clumpiness in the CSM of SN 2002ic.

3. Nova Cavities around Normal Type Ia Supernovae

The blast wave from a nova outburst will clear out the region around a white dwarf in any recurrent nova SNIa progenitor. Our model is most relevant for systems where one might otherwise expect the presence of a significant amount of hydrogen. Here we consider such a system consisting of a near-Chandrasekhar mass white dwarf accreting material from a red giant companion at a suitable rate to generate recurrent novae. When the white dwarf experiences a nova outburst, the blast wave expands freely for a few days, then experiences a several-month Sedov-Taylor phase, and finally enters the momentum-conserving snowplow phase. Observations of the recurrent nova RS Oph suggest $v_{\mathrm{shell}} \approx 4000$ km s^{-1} (Bode 1987), a 2-day free-expansion phase (Sokoloski et al. 2006), and a 2-month Sedov-Taylor phase (Mason et al. 1987). Taking a typical symbiotic-star mass-loss rate of $\dot{M}_{\mathrm{wind}} \sim 10^{-7}$ $M_{\odot}$ yr^{-1} (Seaquist & Taylor 1990), an ejected shell mass of $M_{\mathrm{shell}} = 4 \times 10^{-7}$ $M_{\odot}$ (Hachisu & Kato 2001), an ejected shell velocity of $v_{\mathrm{shell}} = 4000$ km s^{-1}, and a binary separation of 1 AU, the nova blast wave would evacuate a region with radius $\sim 9.9 \times 10^{15}$ cm in 40 years. During this time, the red-giant wind would refill the innermost volume, out to $\sim 1.3 \times 10^{15}$ cm. It would take SNIa ejecta traveling at 10^4 km s^{-1} ~ 15 days to traverse the refilled region and ~ 115 days to reach the outer edge of the cavity. See Table 1 for a summary of these model quantities.

4. Discussion

We propose that recurrent nova outbursts can clear out hydrogen-free regions around the progenitor systems of SNeIa and thus explain the general lack of observed hydrogen in SNeIa as well as the clearly-defined hydrogen-free region around SN 2002ic. Our model provides an explanation for what had previously been seen as a coincidence in the timing of the end of mass-loss in the progenitor system and the explosion of SN 2002ic. The size of the cavity cleared out in SN 2002ic-like events is determined by the time between the last nova outburst and the SN explosion. We attribute the relative rarity of SN 2002ic-like events to the scarcity of binary systems with such extreme mass-loss rates.

Wang et al. (2004) and Deng et al. (2004) both discuss a model for the CSM of SN 2002ic that involves a significant asymmetry in the form of a clumpy disk surrounding the progenitor system. The arguments for this interpretation derive both from spectropolarimetry (Wang et al. 2004) and the late-time observations of high velocities ($\sim 10^4$ km s^{-1}) that are inconsistent with ejecta having been slowed down by interaction with the CSM (Deng et al. 2004). Nova outbursts are also observed to be asymmetric (e.g., Taylor et al. 1989; Anupama & Sethi 1994; Rupen et al. 2006). While the nova outburst-CSM interaction becomes somewhat more complicated in this more complex geometry, the basic principle remains, and the nova blast wave still clears out substantial cavities around the SNIa progenitor. In addition, our model naturally generates large-scale structure that could lead to observed clumpiness in such disks.

Since any near-Chandrasekhar-mass white dwarf accreting at a rate between $\sim 10^{-8}$ and 4×10^{-7} $M_\odot$ yr^{-1} will experience recurrent nova outbursts (Iben 1982; Starrfield et al. 1985; Yaron et al. 2005), the effect of a nova blast wave on the CSM must be taken into account when interpreting the limits placed by observations on the mass-loss rate of SNIa progenitors. Apparent upper limits on mass-loss rates from the progenitors of SNeIa (assuming a wind speed of $v_{\text{wind}} = 10$ km s^{-1}) include 2–3 $\times$ 10^{-4} $M_\odot$ yr^{-1} (SN 1992A; Schlegel & Petre 1993); 1×10^{-7} $M_\odot$ yr^{-1} (SN 1986G; Eck et al. 1995); and 9×10^{-6} $M_\odot$ yr^{-1} (from the unusual SN 2000cx; Lundqvist et al. 2003). Recent work by Panagia et al. (2006) from VLA observations of 27 SNeIa resulted in more a more constraining upper limit of 3×10^{-8} $M_\odot$ yr^{-1} (assuming a steady outflow with $v_{\text{wind}} = 10$ km s^{-1}). These findings would appear to rule out many classes of single-degenerate progenitors. However, if the action of prior novae is taken into account, typical mass-loss rates for single-degenerate SNIa progenitor models are easily compatible with the aforementioned observations. In Sec. 3 we considered an example system with $\dot{M}_{\text{wind}} = 1 \times 10^{-7}$ $M_\odot$ yr^{-1} that would lead to early and late-time emission that would not have been seen by the observations of Panagia et al. (2006). Even higher mass-loss rates of up to $\sim 10^{-6}$ $M_\odot$ yr^{-1} are allowed if correspondingly more massive shells

are ejected in the nova outbursts.

The radius of the cleared-out cavity is a function of the mass-loss rate of the progenitor system. The different evolutionary stages of the companion stars to the white dwarf in SNIa progenitor systems lead to qualitatively different wind mass-loss rates. These different companion stars (e.g., first-ascent red giant vs. AGB) can explain the distinctly different behavior of normal SNeIa and SN 2002ic-like events.

We encourage radiative-hydrodynamic modeling to properly explore the effect of multiple nova outbursts on the density structure of the surrounding CSM. Our model suggests that SN ejecta-CSM interaction should be observable at late times for normal SNeIa but also that the strength of the observed signal from such interaction would be much lower than that for SN 2002ic. The interaction of the SN ejecta with the wind blown since the last nova outburst can also produce an observable signal at early times. While such early interaction may not significantly affect the observed lightcurve due to the limited amount of CSM involved, Gerardy et al. (2004) and Mazzali et al. (2005) suggest that high-velocity spectroscopic features would be signs of SN ejecta-CSM interaction at early times. We urge the observation of SNeIa at both very early and late times to look for high-velocity features, Hα emission, and deviations from the expected exponential decay powered by ^{56}Co. We suggest that interaction of the SN ejecta with the CSM will give rise to such early- and late-time features.

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REFERENCES

Anupama, G. C. & Sethi, S. 1994, MNRAS, 269, 105

Bode, M. F., ed. 1987, RS Ophiuchi (1985) and the recurrent nova phenomenon

Chugai, N. N. & Yungelson, L. R. 2004, Astronomy Letters, 30, 65

Deng, J., Kawabata, K. S., Ohyama, Y., Nomoto, K., Mazzali, P. A., Wang, L., Jeffery, D. J., Iye, M., Tomita, H., & Yoshii, Y. 2004, ApJ, 605, L37

Eck, C. R., Cowan, J. J., Roberts, D. A., Boffi, F. R., & Branch, D. 1995, ApJ, 451, L53+

Fujimoto, M. Y. 1982, ApJ, 257, 767

Gehrz, R. D. & Woolf, N. J. 1971, ApJ, 165, 285

Gerardy, C. L., Höflich, P., Fesen, R. A., Marion, G. H., Nomoto, K., Quimby, R., Schaefer, B. E., Wang, L., & Wheeler, J. C. 2004, ApJ, 607, 391

Hachisu, I. & Kato, M. 2001, ApJ, 558, 323

Hachisu, I., Kato, M., Nomoto, K., & Umeda, H. 1999b, ApJ, 519, 314

Hachisu, I., Kato, M., & Nomoto, K. 1999a, ApJ, 522, 487

Hamuy, M., Maza, J., & Phillips, M. 2002, IAU Circ., 8028, 2

Hamuy, M., Phillips, M., Suntzeff, N., & Maza, J. 2003, IAU Circ., 8151, 2

Hamuy, M., Phillips, M. M., Suntzeff, N. B., Maza, J., González, L. E., Roth, M., Krisciunas, K., Morrell, N., Green, E. M., Persson, S. E., & McCarthy, P. J. 2003, Nature, 424, 651

Han, Z. & Podsiadlowski, P. 2006, MNRAS, 447

Iben, I. 1982, ApJ, 259, 244

Hillebrandt, W. & Niemeyer, J. C. 2000, ARA&A, 38, 191

Iben, I. & Renzini, A. 1983, ARA&A, 21, 271

Imshennik, V. S. & Dunina-Barkovskaya, N. V. 2005, Astronomy Letters, 31, 528

Kudritzki, R. P. & Reimers, D. 1978, A&A, 70, 227

Livio, M. & Truran, J. W. 1992, ApJ, 389, 695

Livio, M. 2001, "Supernovae and Gamma-Ray Bursts: The Greatest Explosions since the Big Bang", Cambridge University Press

Livio, M. & Riess, A. G. 2003, ApJ, 594, L93

Lundqvist, P., Sollerman, J., Leibundgut, B., Baron, E., Fransson, C., & Nomoto, K. 2003, in From Twilight to Highlight: The Physics of Supernovae, ed. W. Hillebrandt & B. Leibundgut, 309

Mason, K. O., Córdova, F. A., Bode, M. F., & Barr, P. 1987, in RS Ophiuchi (1985) and the Recurrent Nova Phenomenon, ed. M. F. Bode, 167

Mazzali, P. A., Benetti, S., Altavilla, G., Blanc, G., Cappellaro, E., Elias-Rosa, N., Garavini, G., Goobar, A., Harutyunyan, A., Kotak, R., Leibundgut, B., Lundqvist, P., Mattila, S., Mendez, J., Nobili, S., Pain, R., Pastorello, A., Patat, F., Pignata, G., Podsiadlowski, P., Ruiz-Lapuente, P., Salvo, M., Schmidt, B. P., Sollerman, J., Stanishev, V., Stehle, M., Tout, C., Turatto, M., & Hillebrandt, W. 2005, ApJ, 623, L37

Nomoto, K., Suzuki, T., Deng, J., Uenishi, T., & Hachisu, I. 2005, in ASP Conf. Ser. 342: 1604-2004: Supernovae as Cosmological Lighthouses, ed. M. Turatto, S. Benetti, L. Zampieri, & W. Shea, 105

Panagia, N., Van Dyk, S. D., Weiler, K. W., Sramek , R. A., Stockdale, C. J., & Murata, K. P. 2006, astro-ph/0603808

Prialnik, D., Livio, M., Shaviv, G., & Kovetz, A. 1982, ApJ, 257, 312

Prieto, J., Garnavich, P., Depoy, D., Marshall, J., Eastman, J., & Frank, S. 2005, IAU Circ., 8633, 1

Rupen, M. P., Mioduszewski, A. J., & Sokoloski, J. L. 2006, ApJ

Schlegel, E. M. & Petre, R. 1993, ApJ, 412, L29

Seaquist, E. R. & Taylor, A. R. 1990, ApJ, 349, 313

Sokoloski, J. L., Luna, G. J. M., Mukai, K., & Kenyon, S. J. 2006, Nature *in press*, astro-ph/0605326

Starrfield, S., Sparks, W. M., & Truran, J. W. 1985, ApJ, 291, 136

Taylor, A. R., Davis, R. J., Porcas, R. W., & Bode, M. F. 1989, MNRAS, 237, 81

Wang, L., Baade, D., Höflich, P., Wheeler, J. C., Kawabata, K., & Nomoto, K. 2004, ApJ, 604, L53

Wheeler, J. C. 2002, American Journal of Physics, 71, 11

Wood-Vasey, W. M. 2002, IAU Circ., 8019, 1

Wood-Vasey, W. M., Wang, L., & Aldering, G. 2004, ApJ, 616, 339

Yaron, O., Prialnik, D., Shara, M. M., & Kovetz, A. 2005, ApJ, 623, 398

Table 1.   Model parameters

Model	Binary Separation [AU]	$\dot{M}_{\mathrm{wind}}$ [$M_\odot$/year]	M_{shell} [$M_\odot$]	v_{shell} [km/s]	v_{SN} [km/s]	Δt_{nova} [years]	Cavity Extent Inner [10^{15} cm]	Outer
SN 2002ic	10	10^{-3}	1×10^{-6}	4000	10^4	14	0.44	1.5
WD+RG $\Rightarrow$ SNIa	1	10^{-7}	4×10^{-7}	4000	10^4	40	1.3	9.9

Note. — Model parameters for the nova outburst clearing mechanism for the case of SN 2002ic and for a more generic SNIa progenitor system consisting of a white dwarf with a red giant companion. See text for more detail on the parameter definitions.